LCA Methodology

Application of Markov Chain Model to Calculate the Average Number of Times of Use of a Material in Society

An Allocation Methodology for Open-Loop Recycling

Part 2: Case Study for Steel

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Preamble. In this series of two papers, a methodology to calculate the average number of times a material is used in a society from cradle to grave is presented and applied to allocation of environmental impact of virgin material. **Part 1 – Methodology Development** [Int J LCA 11 (5) 354–360] focused on methodology development and showed how the methodology works with hypothetical examples of material flows. **Part 2** presents case studies for steel recycling in Japan, in which the methodology is applied and allocation of environmental impact of virgin steel is conducted.

Abstract

Goal, Scope and Background. The life cycle of steel begins with the mining of iron ore from the earth. Steel is produced in steel works and used in various products. Some of the steels are recycled at the products' end of life and used as a resource for the production of new steel in electric furnaces, while the remaining steel is used just once in products before being discarded (landfilled). In this paper, case studies were conducted to analyze the average number of times the element of iron is used and its residence time in society, in which the methodology developed in Part 1 of the paper was applied. CO_2 emissions caused by steel productions and recycling were allocated by the number of times the element of steel is used in a society.

Results and Discussion. On the basis of the material flows of steel in Japan in 2000, it was calculated that at least 70% of the BF crude iron produced in Japan in 2000 was ultimately exported. On the assumption that steel is used in other countries in the same way as it is in Japan, the average number of times of use and the residence time of elemental iron in society are 2.67 and 62.9 years, respectively. Both of these values depend significantly on the recycling ratios of steel from construction and automobiles. Our model indicated that if the recycling ratio of steel from civil engineering and construction increased from 50% to 60%, the average number of times used would increase to 3.17 and the residence time of elemental iron in society would increase to 75.8 years. If CO_2 emissions caused by steel productions and recycling are allocated by the number of times the element of steel is used in a society, it was calculated that steel use of one time generates in average an environmental burden of 1.03 t-CO_2/t.

Conclusion. A method was developed to calculate the average number of times a material is used in a society from cradle to grave. Our methodology is based on Markov chain model using matrix-based numerical analysis, and has been successfully applied to steel. The results obtained by this methodology, i.e. the average number of times the element of iron is used in society, could be used for allocation of environmental burdens of virgin material as well as an indicator for assessing the state of material use in a certain year, based on material flow of material in that year.

Recommendation and Perspective. It is recognized that further researches must be conducted to gather data on steel production, use, and recovery in other countries and incorporate them into the transition probability matrix to obtain more precise results. Although this paper deals only with steel, this method can also be applied to other materials.

Keywords: Markov chain; material flow; number of times of use; open loop recycling management; residence time; steel

Introduction

In this paper, Part 2 of the series of papers, case studies have been conducted to analyze the average number of times steel is used from cradle to grave. The life cycle of steel begins when iron ore is extracted from the earth. Mined iron ore is used as raw material in the production of blast furnace (BF) crude iron, followed by the production of BF steel products at integrated steel mills. Some BF steel products are discarded (landfilled) after being used in products once, while some are recovered after use in the products and recycled as the resource for electric furnace (EF) steel products. Similarly, some EF steel products are recovered after use in products and again recycled or landfilled. When recycling, the element of iron (atoms) in the steel is used again in other products. The concern is how many times the element of steel is used in a society from cradle (resource extraction) to grave (landfill).

The objective of this paper is to examine the residence status of the element of iron in Japan, specifically to calculate the average number of times the element of iron is used until BF crude iron produced in integrated steel mills (virgin steel) in Japan is discarded (landfilled) or exported. However, as explained later, there is a high probability that BF crude iron produced in Japan will be exported without being landfilled in Japan. Therefore, on the assumption that steel is used in the same way in other countries as it is in Japan, this case study also calculates the average number of times the element of iron is used until Japanese BF crude iron is ultimately discarded (landfilled) somewhere in the world.

In addition, the followings were conducted in this paper.

1) Calculation of average residence time of the elements of iron in society
2) Sensitivity analysis, the effect of the increase in recovery rate of iron scraps from post consumer products on the average number of times the element of iron is used and its residence time in society
3) Allocation of environmental impact (CO_2 emissions) of BF crude iron based on the average number of times the element of iron is used

Calculation of residence time of the elements of iron in society is not the main objective of this paper. However, this value is also interesting as an indicator of sustainable use of a material. In the sensitivity analyses, two aspects were investigated. One is the effect where the recovery rate of iron scraps from post consumer products was simply increased. The other is the effect where the ratio of closed loop recycling of post consumer products was increased while the total recovery rate of iron scraps from post consumer products was constant.

1 Analyzing the Average Number of Times the Element of Iron is Used and its Residence Time in Society

1.1 Modeling elemental iron's status of residence in society

The state of element of iron in Japan and its flow can be modeled as shown in **Fig. 1**.

In this paper, it was assumed that the element of iron enters Japan as a natural resource (iron ore) and all becomes BF crude iron in integrated mills, which is used for producing BF steel and further used in products.

As it is shown in Fig. 1, the element of iron takes various forms, and the probabilities that the element in one state will become in another state as shown by the arrows in Fig. 1 depends on the processes involved between the states. These values will be constant as long as there are no changes in the processes. The probability that the element of steel used in products will undergo to its next state (landfill or obsolete

scrap) differs considerably from one product to another, and depends mainly on the recovery rate of steel scraps from post-consumer products. Hence, this paper divides steel products into five categories by application: construction, machine, automobile, container, and other. It was also assumed that when obsolete scrap is used for producing EF steel products, there are no differences in application that are attributable to source. Actually, obsolete scraps with high content of copper tend to be used for EF steel products for construction. These detailed analyses reflecting the differences of use of obsolete scraps in application will be future works.

Some elements of iron leave Japan through exports, for which the study took into account the export in the forms of crude iron, steel products, scraps and indirect export of steels by products' export. It did not consider inputs of industrial and obsolete scrap to converters, whose volumes seems be very small. Iron in slag from iron mills was likewise not considered because the amount is very small [1].

Based on the foregoing, the residential states of element of iron in Japan were put into 13 categories: BF crude iron, converter in-house scrap, BF steel products, construction steels, machine steels, automobile steels, container steels, other steels, obsolete scrap, EF crude iron, EF in-house scrap, EF steel products and industrial scrap. Adding 'exports' and 'landfill' created a total of 15 categories of states.

1.2 Preparation of state-transition tables based on material flow

Based on the above categorization of 15 states, a state-transition table for element of iron was created from the material flow. **Table 1** shows the state-transition table created for material flow of iron in Japan in FY2000, which illustrates how the element of iron changes from the states shown in rows to those shown in columns.

Line 1 shows the amounts of BF crude iron that change to other states. Line 2 shows the amounts of BF in-house scrap that change to other states. Line 3 shows BF steel products, their exports and the amount that goes into industrial scraps. Lines 4 through 8 show the amounts of steel products that are recovered from products (5 categories) and become obsolete scraps, and those which are not recovered (landfilled). Line 9 shows the amounts of obsolete scraps that become EF crude steel and exports. Line 10 shows the amount of EF crude steel making transitions to other states. Lines 11 and 13 show the amounts of EF in-house scrap and industrial scrap that proceed to the next state. Line 12 shows the amounts of EF steel material that are used in products of various kinds, that are exported, and that become industrial scrap. Lines 14 and 15 give the amounts of exports and waste that change to other states, but all elements are zero because exported and discarded iron remains in those states. How the values in Table 1 were obtained was explained in detail [2].

1.3 Transition probability matrix preparation

This study assumes that when the element of iron makes the transition from one state to the next, the transition is
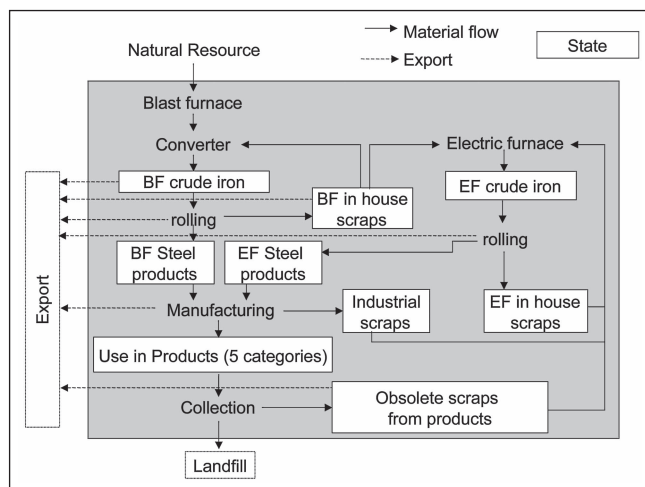

Fig. 1: Material flow and states of the element of iron

Table 1: State-transition table created for material flow of iron in Japan in FY2000 (Unit: 1000 tone)

|		BF crude iron	BF in-house scrap	BF steel products	Use in construction	Use in machines	Use in cars	Use in containers	Use in other products	Obsolete scrap	EF crude iron	EF in-house scrap	EF steel products	Industrial scrap	Exports	Landfill	Total
1	BF crude iron	0	7,457	45,421	0	0	0	0	0	0	0	0	0	0	23,998	0	76,876
2	BF in-house scrap	6,825	0	0	0	0	0	0	0	0	428	0	0	0	204	0	7,457
3	BF steel products	0	0	0	9,147	3,353	8,887	1,269	2,462	0	0	0	0	6,802	13,502	0	45,421
4	Use in construction	0	0	0	0	0	0	0	0	8,202	0	0	0	0	0	8,202	16,404
5	Use in machines	0	0	0	0	0	0	0	0	5,200	0	0	0	0	0	1,300	6,500
6	Use in cars	0	0	0	0	0	0	0	0	7,712	0	0	0	0	0	857	8,568
7	Use in containers	0	0	0	0	0	0	0	0	1,324	0	0	0	0	0	110	1,435
8	Use in other products	0	0	0	0	0	0	0	0	2,760	0	0	0	0	0	690	3,450
9	Obsolete scrap	0	0	0	0	0	0	0	0	0	22,324	0	0	0	2,874	0	25,198
10	EF crude iron	0	0	0	0	0	0	0	0	0	0	2,977	27,348	0	3,578	0	33,903
11	EF in-house scrap	0	0	0	0	0	0	0	0	0	2,977	0	0	0	0	0	2,977
12	EF steel products	0	0	0	17,060	1,529	1,921	153	1,771	0	0	0	0	1,031	3,882	0	27,348
13	Industrial scrap	0	0	0	0	0	0	0	0	0	8,663	0	0	0	0	0	8,663
14	Export	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Landfill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

uniquely determined on the basis of a probability obtained from the state-transition table (see Table 1), and it employs the Markov chain model. According with the methodology presented in Part 1 of this paper, a transition probability matrix **A** (**Table 2**) for the element of iron was prepared from the state-transition table.

1.4 Calculating the average number of times the element of iron is used and its average residence time in society

According with the calculation procedure explained in Part 1 of this paper, the average number of times the element of iron is used was calculated [3]. Some differences are that W in Eqs. 6 and 7 indicates not only the state of landfill but also export.

Table 2: Transition probability matrix **A** for iron by state (FY 2000)

	BF crude iron	BF in-house scrap	BF steel products	Use in construction	Use in machines	Use in cars	Use in containers	Use in other products	Obsolete scrap	EF crude iron	EF in-house scrap	EF steel products	Industrial scrap	Exports	Landfill
BF crude iron	0.00	0.10	0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00
BF in-house scrap	0.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.03	0.00
BF steel products	0.00	0.00	0.00	0.20	0.07	0.20	0.03	0.05	0.00	0.00	0.00	0.00	0.15	0.30	0.00
Use in construction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.50
Use in machines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.20
Use in cars	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.00	0.10
Use in containers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.92	0.00	0.00	0.00	0.00	0.00	0.08
Use in other products	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.20
Obsolete scrap	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.11	0.00
EF crude iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.81	0.00	0.11	0.00
EF in-house scrap	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
EF steel products	0.00	0.00	0.00	0.62	0.06	0.07	0.01	0.06	0.00	0.00	0.00	0.00	0.04	0.14	0.00
Industrial scrap	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Export	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Landfill	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
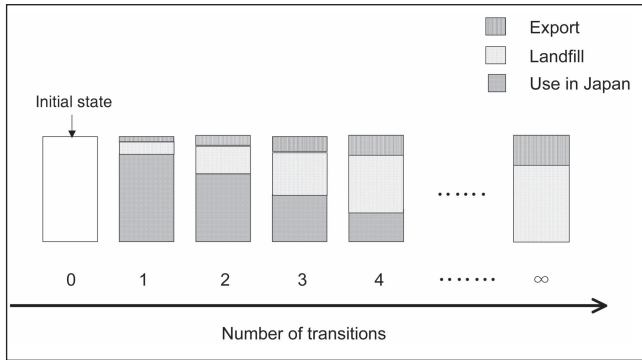
Fig. 2: Diagram of state transitions of the element of iron with number of transitions

Here the average number of times that element of iron is used in Japan is defined as "the number of times it is used in five product categories divided by application". The states of BF crude iron, steel products, and scrap are the states of their residence in society, but these are not included in the number of times used. If the set of states used in the five applications (elements 4 through 8 in Table 1) is defined as U, the average number of times used in Japan from the initial state s until ultimately being exported or discarded (landfilled) through an unlimited number of transitions can be derived by Eq. 8.

Fig. 2 shows the number of times that the element of iron is used derived by Eq. 5, starting after its input in Japan at initial state s until it is either exported from Japan or landfilled.

After exported iron is used in its importing country, it is discarded or again exported. It is assumed in this study that the structures of steel production and consumption are the same in other countries as they are in Japan; thus, this study calculated the number of times used until all the elements of

iron produced and input in Japan at initial state s have ultimately been discarded. In those calculations, the element of iron in importing countries has the same state-transition probabilities as in Japan. Although transition probability matrix **A** has a state called 'exports', it is necessary to prepare a new transition probability matrix from which this item has been deleted because exporting is merely a process that connects one state with another. For this reason a transition probability matrix **B** was prepared according to the following procedure, and the average number of times used was calculated using the same derivation method in Part 1 of this paper.

1) Delete the 'Exports' row and column from the 15-row, 15-column state-transition matrix (see Table 1), and create a state-transition table with the other 14 rows and 14 columns being the same.
2) Calculate the row sums.
3) Use Eq. 1 to prepare transition probability matrix **B** having 14 rows and 14 columns (**Table 3**).

Apart from the average number of times used, average residence time of the elements of iron in society was also calculated in this paper. **Table 4** shows the recovery ratio of steel scrap [4] and the average lifetimes of products in the five applications [5].

Table 4: Recovery ratio of steel scrap and average lifetime of the products in each application

Application	Recovery ratio of steel scrap [%]	Average Lifetime [Years]
Construction	50.0	30
Machines	80.0	12
Automobiles	90.0	13
Containers	92.3	1
Other	80.0	12

Table 3: Transition probability matrix **B** for iron by state (FY 2000)

	BF crude iron	BF in-house scrap	BF steel products	Use in construction	Use in machines	Use in cars	Use in containers	Use in other products	Obsolete scrap	EF crude iron	EF in-house scrap	EF steel products	Industrial scrap	Landfill
BF crude iron	0.00	0.14	0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BF in-house scrap	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
BF steel products	0.00	0.00	0.00	0.29	0.11	0.28	0.04	0.08	0.00	0.00	0.00	0.00	0.21	0.00
Use in construction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.50
Use in machines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.20
Use in cars	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.10
Use in containers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.92	0.00	0.00	0.00	0.00	0.08
Use in other products	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.20
Obsolete scrap	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
EF crude iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.90	0.00	0.00
EF in-house scrap	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
EF steel products	0.00	0.00	0.00	0.73	0.07	0.08	0.01	0.08	0.00	0.00	0.00	0.00	0.04	0.00
Industrial scrap	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Landfill	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

These indicate the average residence years of elements of iron in products. Residence time of the elements of iron in other state, such as BF crude iron and scraps, are relatively negligible compared with those in products. Therefore, if we define the average residence time in society T_u in each state u, Eq. 1 can calculate the average residence time of elements of iron in society from initial state s until ultimately being landfilled after an unlimited number of transitions.

$$T_s = \sum_{u \in U} T_u N_{su} \qquad \qquad \text{(Eq. 1)}$$

2   Results and Discussion

2.1   Calculation of average number of times used and average residence time in society

Transition probability matrix **A** for FY2000 (see Table 2) was used to calculate the number of times used in each application (N_{su}), the total average number of times used (t_s), the average residence time in Japan (T_s), and the probability of ultimately being exported or discarded (landfilled) (P_{sj}), occurring after the production and input of element of iron as BF crude iron in Japan. Results appear in **Table 5**. The total average number of times used came to 0.769, and the average residence time in Japan was 17.1 years. The probability that the element of iron will ultimately be exported after being input as BF crude iron was 0.732, which is far larger than the 0.268 probability that it will be landfilled in Japan. The number of times used is less than 1 because the number of times that exported steel is used is not taken into account.

Therefore, transition probability matrix **B** (see Table 3) was used to calculate the number of times used in each application (N_{su}), the average number of times used (t_s), and the average residence time in society (T_s) until all the elements of iron are completely discarded (landfilled). Results appear in **Table 6**. The average number of times used came to 2.67, and the average residence time in society was 62.9 years.

Examining the number of times used according to application, it can be seen that construction was the highest at 1.72 times, followed by automobiles at 0.438 times. Construction has a large value because of its high rate of consumption of steel scraps in making EF steel products for this application.

2.2   Sensitivity analysis

As the rates of recovery and reuse of steel scraps increase, the average number of times the element of iron is used and its residence time in society are expected to increase. Therefore, sensitivity analyses were conducted to investigate the magnitude of change in the average number of times used and the residence time in society, when the recovery rates of steel scrap from the five products divided by applications are increased by one percentage point. Results appear in **Fig. 3**.

With the increase in the recovery rate from each product category by one percentage point, the average number of times used increased. The largest change was observed in construction (a rise of 0.04 times/percentage point), followed by automobiles (0.01 times/percentage point). The average residence time in society increased by 1.1 years/percentage point for construction and 0.27 years/percentage point for automobiles. Further, it was found that raising the recovery
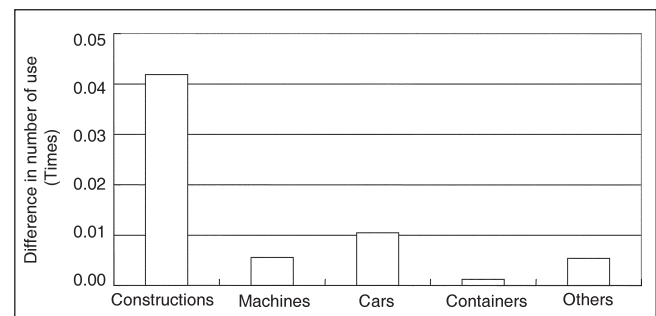
Fig. 3: Effect of increasing the collection ratio (by 1 percentage point) on the average number of times used and residence time of element of iron in each product

Table 5: Results for the number of times used in each application (N_{su}), the total average number of times used (t_s), the average residence time in society (T_s), and the probability of ultimately being exported or discarded (P_{sj}), occurring after the production and input of element of iron as BF crude iron in Japan

Items	N_{su}: Average number of times used in each prodct					P_{sj}: Probability of final state		t_s: Total average number of times used in all products	T_s: Average residence time in use (years)
	Use in construction	Use in machines	Use in cars	Use in containers	Use in other products	Exports	Landfill		
Results	0.443	0.076	0.162	0.021	0.068	0.732	0.268	0.769	17.1

Table 6: Results for the number of times used in each application (N_{su}), the average number of times used (t_s), and the average residence time in society (T_s) until all the elements of iron are completely discarded (landfilled)

Items	N_{su}: Average number of times used in each state					t_s: Total average number of times used in all states	T_s: Average residence time in use (years)
	Use in construction	Use in machines	Use in cars	Use in containers	Use in other products		
Results	1.72	0.233	0.438	0.052	0.226	2.67	62.9

rate from 50% to 60% for construction steel, the average number of times used and residence time in society increased 3.17 times and 75.8 years, respectively.

Next, another sensitivity analysis was conducted to investigate the effect where the ratio of closed loop recycling of post consumer products was increased while the total recovery rate of iron scraps from post consumer products was constant. Container steels were taken as an example. At present, the total recovery rate of steel scrap from container is 92.3%, while it is found that the present closed loop recycling ratio of steel scrap from container is only 0.516% stochastically. It was calculated the average number of times the element of iron is used increased by 6.32×10^{-5} times/percentage point when the closed loop recycling ratio of steel scrap from container is increased. So, little influence was observed compared with the influence when the total recovery rate from containers was increased by one percentage point.

2.3 Allocation of environmental impact (CO_2 emissions) of BF crude iron based on the average number of times the element of iron is used

As stated previously, the element of iron input in Japan as BF crude iron in 2000 is used an average of 2.67 times in products until it is completely discarded. During that time the element of iron is manufactured as BF steel products 0.99 time and as EF crude steel 1.98 times. As steel scrap subjected to separation and recycling processes is probably obsolete scrap only because BF in-house scraps and industrial scraps will go into EF without any separation and recycling processes, separation and recycling process is conducted 1.67 times. The amounts of CO_2 generated during BF steel product manufacturing, separation and recycling process and EF steel manufacturing were, 1.679, 0.048, and 0.499 t-CO_2/t, respectively [6]. Dividing the total weight of CO_2 generated in the life cycle (2.75) by the average number of times used (2.67) determined that 1.03 t CO_2 are generated each time 1 t of steel is used. Increasing the recovery rate of construction steel by 10 percentage points from 50% resulted in 0.954 t of CO_2 generated when using 1 t of steel, for a reduction of about 7%.

3 Conclusion

In this paper, case studies were conducted to analyze the average number of times the element of iron is used and its residence time in society. It was found that at least 70% of the converter crude steel produced in Japan in 2000 was ultimately exported. On the assumption that steel is used in other countries in the same way as it is in Japan, and by seeking the average number of times that BF crude iron produced in Japan is used and its average residence time in society until being completely discarded, it was found that:

1) The average number of times used and average residence time in society were, respectively, 2.67 times and 62.9 years under the steel consumption structure in Japan of 2000.

2) The construction steel recovery rate greatly affects the cyclical use of steel. Raising the recovery rate of construction steel from 50% to 60% results in values of 3.17 for the average number of times used and 75.8 years for the average residence time in society.

3) Little influence on the average number of times the element of iron is used and average residence time in society was observed when the closed loop recycling ratio of steel scrap from container is increased.

4) Using steel one time generates an environmental burden of 1.03 t-CO_2/t.

It is recognized that further researches must be conducted to gather data on steel production, use, and recovery in other countries and incorporate them into the transition probability matrix to obtain more precise results. Although this paper deals only with steel, this method can also be applied to other materials.

Finally, the authors clarify that the main results of this paper, the average number of times the element of iron is used, are based on Japan's material flow of iron in a certain year. It does not determine the actual number of times the element of steel is used in society based on the production history, history of use of steel by application (products), or recycling rates of past years.

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